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Seismic Behavior of Glass Fiber-Reinforced Polymer Wall Panels

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Abstract
Glass Fiber-Reinforced Polymer (GFRP) panels have been increasingly used for structural applications due to their light weight, corrosion resistance and construction-easiness. This study evaluates the seismic performance of GFRP wall panels based on comprehensive shaking table tests and Finite Element Analysis (FEA). A GFRP wall panel is experimentally subjected to harmonic ground motions of frequencies ranging from 10 to 15 Hz. A mass is attached to the top of the panel to simulate gravitational weight. The panel remains undamaged under a peak base acceleration of 2.1 g. Its FEA is conducted using Abaqus based on Rayleigh damping. There is a good correlation between the experimental and FEA results. Another FEA model is developed to study the seismic behavior of a Reinforced Concrete (RC) wall, which is validated by results from an existing study. The two FEA models are then used to compare the seismic performance of GFRP wall panels versus RC walls in terms of drift ratio and hysteretic behavior. It is found that while GFRP wall panels cannot replace RC walls in multi-story buildings due to their low stiffness, their performances are comparable to RC walls for low-rise buildings. Therefore, GFRP wall panels can be potentially used in low-rise buildings in seismic regions.

Keywords
Fiber-Reinforced Polymer (FRP), Wall panel, Seismic behavior, Shaking table test, Finite element modeling, Reinforced Concrete wall

Disciplines
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SEISMIC BEHAVIOR OF GLASS FIBER-REINFORCED POLYMER WALL PANELS

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ABSTRACT

Glass Fiber-Reinforced Polymer (GFRP) panels have been increasingly used for structural applications due to their light weight, corrosion resistance and construction-easiness. This study evaluates the seismic performance of GFRP wall panels based on comprehensive shaking table tests and Finite Element Analysis (FEA). A GFRP wall panel is experimentally subjected to harmonic ground motions of frequencies ranging from 10 to 15 Hz. A mass is attached to the top of the panel to simulate gravitational weight. The panel remains undamaged under a peak base acceleration of 2.1 g. Its FEA is conducted using Abaqus based on Rayleigh damping. There is a good correlation between the experimental and FEA results. Another FEA model is developed to study the seismic behavior of a Reinforced Concrete (RC) wall, which is validated by results from an existing study. The two FEA models are then used to compare the seismic performance of GFRP wall panels versus RC walls in terms of drift ratio and hysteretic behavior. It is found that while GFRP wall panels cannot replace RC walls in multi-story buildings due to their low stiffness, their performances are comparable to RC walls for low-rise buildings. Therefore, GFRP wall panels can be potentially used in low-rise buildings in seismic regions.

KEYWORDS:

Fiber-Reinforced Polymer (FRP), Wall panel, Seismic behavior, Shaking table test, Finite element modeling, Reinforced Concrete wall

1. INTRODUCTION

Fiber-reinforced polymer (FRP) materials have been widely used in civil engineering. While they are more commonly used to strengthen existing structures [1-2], FRP components have gained popularity in recent years because they are easy to retrofit and reduce the overall self-weight of the structure, yielding design flexibility.

While early research work mainly focused on the static behavior of FRP (e.g., Clarke [3]; Davalos *et al*. [4]), there has been some recent studies on their dynamic behavior through analytical and experimental investigations [5-8]. In particular, Mosallam *et al*. [9] conducted a comprehensive study on the pultruded GFRP beam-to-column connections under both static and dynamic loads, suggesting that GFRP connections could be modeled as semi-rigid in frame analysis. Boscato and Russo [10-12] used the free vibration response of a large FRP space frame to identify its structural information including fundamental frequencies, mode shapes and damping coefficients. Yang *et al*. [13] researched the dynamic and fatigue performances of a pultruded FRP frame, concluding that FRP components showed no significant degradation after 2.1 million cycles of fatigue load. Bai and Keller [14] studied the dynamic structural response of an all-FRP pedestrian bridge under impact and human walking excitations with output-only identification techniques. More recently, Zhang *et al.* [15] investigated the cyclic performance of tubular FRP beam-column bonded sleeve connections, which could achieve good ductility and energy dissipation capacity; Ding et al. [16] applied a constant axial load and a cyclic lateral load to composite frames and achieved satisfactory seismic performance. While these studies represent pioneer work in furthering the understanding of the dynamic behavior of FRP components, to the best of the authors' knowledge, the seismic behavior of FRP panels as load-bearing walls is yet to be studied.

Previously, FRP panels were mainly for bridge decks and building floors. For example, Zi *et al.* [17] proposed a GFRP deck panel with rectangular holes filled with foam to improve deck strength and stiffness. Satasivam *et al.* [18-21] conducted research on modular FRP sandwich panels for building floors, which consisted of FRP pultruded boxes bonded with two GFRP plates. The authors demonstrated that foam filling, adhesive bonding, and bidirectional pultrusion orientation improved the flexural load-bearing capacity of the panels. The FRP sandwich panels could also be bolted to steel beams to form composite beam and slab systems. In this study, the authors investigate FRP panels as structural walls, where the axial and shear loading capacity of FRP panels is of interest. Reinforced Concrete (RC) shear wall is the most widely used wall type to resist lateral loads. Extensive research on the seismic performance of RC walls has been conducted experimentally [22, 23] and numerically [24]. The inelastic seismic response of RC walls is complex because it includes multiple vibration modes in the nonlinear range, the post-elastic behavior of concrete and steel under dynamic loading, and the interactions among flexural, shear, and axial cyclic loadings. Compared to traditional RC walls, FRP wall panels have some advantages. Due to its high strength-to-weight ratio, easy application, and resistance to corrosion, FRP materials have been applied to enhance existing structural walls' strength and ductility [25]. However, unlike RC walls, FRP wall panels do not yield and have relatively low stiffness. A question arises whether FRP panels are suitable for seismic mitigation, and how their performance would compare with RC walls.

Shaking table testing is often recognized as the most suitable experimental method for reproducing the effects of earthquakes on structrual members. In this paper, the dynamic behavior of a pultruded GFRP wall panel exposed to seismic loads is experimentally studied through a shaking table test. Results from the laboratory tests are used to model the behavior of

GFRP units, which are used to compare the seismic performance of GFRP wall panels with that of structural RC shear walls.

The rest of the paper is organized as follows. Section 2 describes the GFRP panel used in the laboratory and reports mechanical properties obtained experimentally from the static and free vibrations tests. Section 3 reports the results from the laboratory testing of a GFRP wall panel exposed to harmonic ground motions using a shaking table. Section 4 compares the dynamic characteristics of the wall obtained through free vibration and shaking table tests with the results from the FEA analysis. Section 5 creates and validates an FEA model of an RC wall, and uses this model to compare the response of RC walls with that of GFRP walls under seismic loads. Section 6 concludes the paper by discussing results and potential applications of GFRP structures.

2. GFRP PANEL PROPERTIES

The panel used in this study is a Composolite® building panel provided by Strongwell®. It is 61 cm wide by 122 cm long made of glass fiber using a pultrusion process. The geometry of the panel is shown in Figure 1. The manufacturer's values of out-of-plane and in-plane moment of inertia are 6.62×10^2 cm^4 and 176×10^2 cm^4, respectively. The thickness of the GFRP panel is 0.297 cm for the outer wall, and 0.218 cm for the separation between the cells. The weight of the whole panel is 13.6 kg.

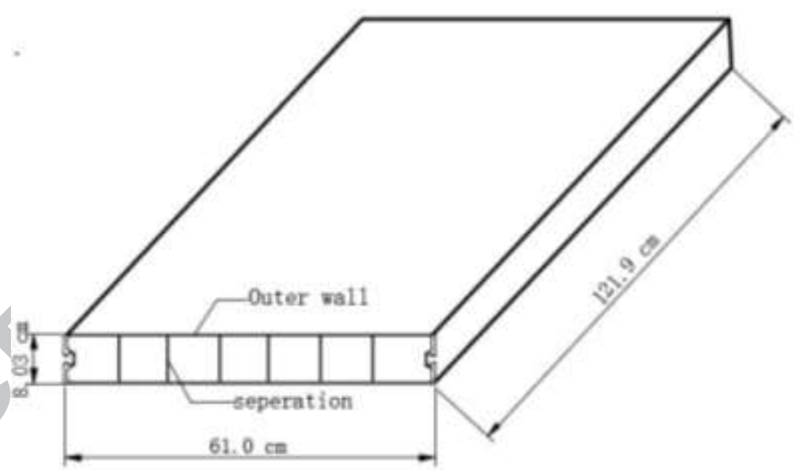


Figure 1. Geometry profile of GFRP panel

Two static tests are conducted to determine the lateral stiffness of the GFRP panel. The first test is a pushover test, as schematized in Figure 2a, where the bottom of the panel is fixed to the ground, and an increasing concentrated force is exerted at the top of the panel. The displacement at the top is recorded by a Linear Variable Differential Transformer (LVDT) with an MEGADAC data acquisition system at a sampling rate of 2000 Hz. The second test consists of a three-point bending test, as schematized in Figure 2b. The panel is configured as a simply supported beam, and a concentrated force is applied at mid-span where another LVDT is installed. The lateral and bending stiffnesses are calculated from the force-displacement relationship using Equation (1) and Equation (2), respectively:

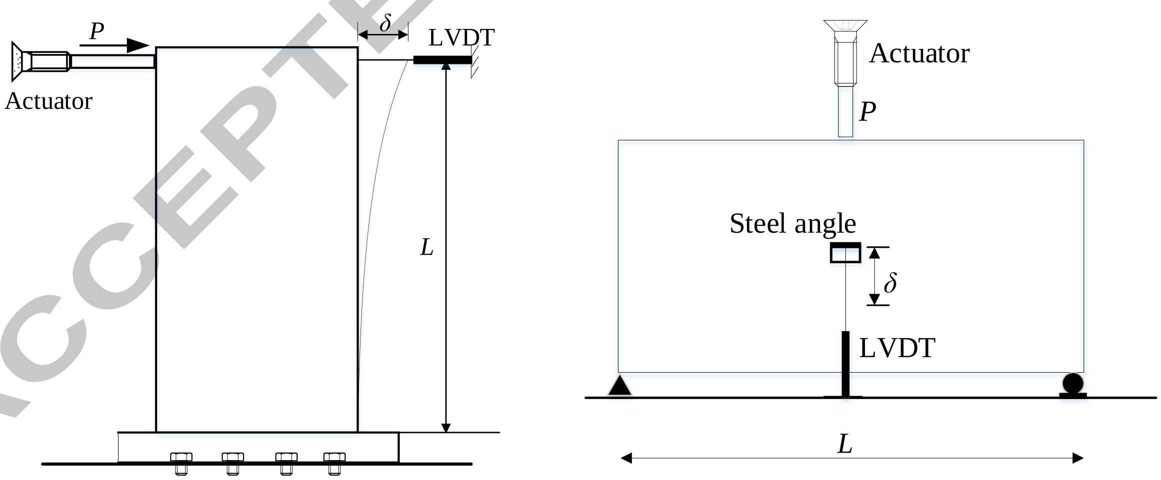
$$EI = \frac{PL^3}{48\delta} \tag{1}$$

$$EI = \frac{PL^3}{3\delta} \tag{2}$$

where EI is the in-plane stiffness calculated from the push-over test or three-point bending test, P is the force applied at the top or middle of the panel, δ is the displacement under that force, and L is the vertical length of the panel, as illustrated in Figure 2. Table 1 lists the results, compared with properties reported by the manufacturer. The test results are lower than manufacturer's data because the width versus length ratio of the panel is not small enough to be treated as a beam and the plain-section assumption may not be totally valid. Nevertheless, an average value of 5.56 GPa between the pushover and three-point bending test is taken as the component's stiffness. Other GFRP wall's structural characteristics including lateral strength, Young's elastic modulus, and Poisson's ratio are reported by the manufacturer as 169 MPa, 6.10 GPa, and 0.27, respectively.

Table 1. Lateral stiffness of GFRP panel

	Flexural modulus (lengthwise)	Difference from the data reported by manufacturer
From pushover test	5.52 GPa	9.5%
From three-point bending test	5.59 GPa	8.4%



(a) Push-over test (b) Three-point bending test

Figure 2. Test configurations to establish lateral stiffness

The GFRP panel is viewed as a load-bearing wall. A steel block is connected by steel angles to the wall to simulate the seismic weight at the top, as illustrated in Figure 3. This seismic weight corresponds to a flat roof of a typical low-rise building, including the total dead load of the roof and 20% of snow load:

$$W = \frac{\left[DL + 20\%\left(SL\right)\right]A_t}{S_l^2} \tag{3}$$

where W is the attached seismic weight, DL is the dead load, SL is the snow load, A_t is the total tributary area, and S_l is the length scale factor, as listed in Table 2.

Table 2. Seismic load at the panel roof

Dead load DL	Snow load SL	Transverse length	Panel width	Total distributed area A_t	Length scale factor S_l	Scaled seismic weight W
501 Pa	300 Pa	4.5 m	0.61 m	2.7 m^2	1:2.5	0.24 kN

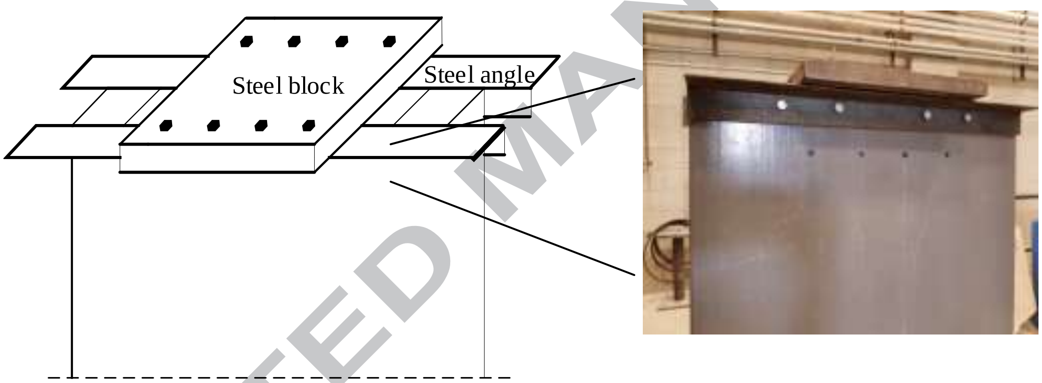


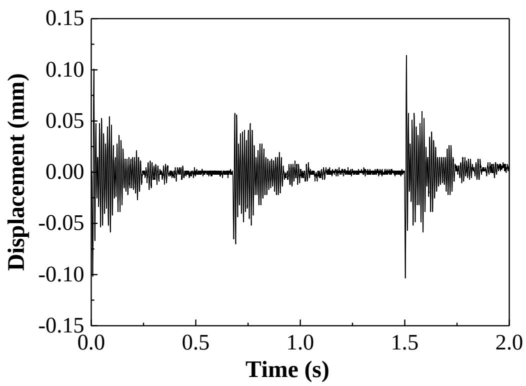
Figure 3. Steel block on the GFRP wall panel

Free vibration tests are conducted to obtain the modal frequencies and damping ratios of the GFRP panel. The bottom of the wall panel is rigidly fixed to the ground, and a plastic hammer is used to excite the panel at random locations. An LVDT and an accelerometer are installed at the top of the panel to record its displacement and acceleration in the lateral direction. The sampling rate for all sensors is 2000 Hz. By analyzing the displacement reponse in the frequency domain, as illustrated in Figure 4, the first natural frequencies of the GFRP panel with and without the attached seismic weight can be identified as 47 Hz and 117 Hz, respectively. These results are consistent with analytical results obtained assuming the GFRP panel as a cantilever beam, which can be predicted by Equations (4) and (5) [26] for the cases with and without seismic weight, respectively, where l is the vertical length of the panel, EI is the in-plane stiffness, m is the mass of the panel, and m_1 is the seismic weight on the top. The first vibration mode shape is similar to a uniform continuous beam under bending, where the deformation increases quadratically with the distance from the base.

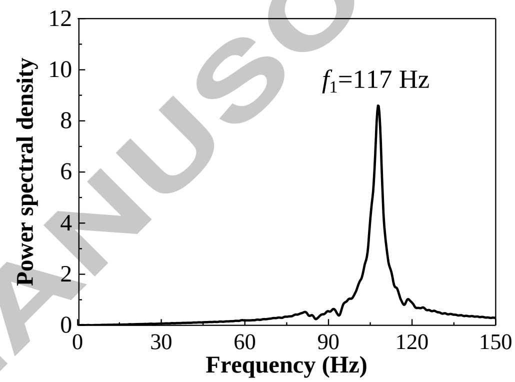
$$f_1 = \frac{1}{2\pi}\frac{6.088}{l}\sqrt{\frac{EI}{\left(3m+12.355m_1\right)l}} = 48\text{Hz} \tag{4}$$

$$f_1^{'} = \frac{1}{2\pi}3.515\sqrt{\frac{EI}{ml^3}} = 128\text{Hz} \tag{5}$$

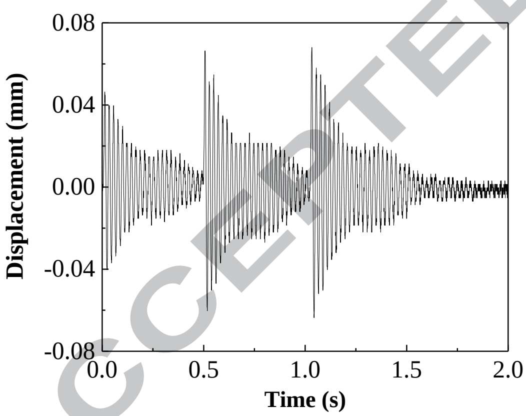
The damping ratio of the structure's first mode is determined by computing the decay of the top displacement after the first ten cycles. It is found to be 0.6%, which is relatively small compared to typical damping ratios for RC (5%) and steel structures (2%).



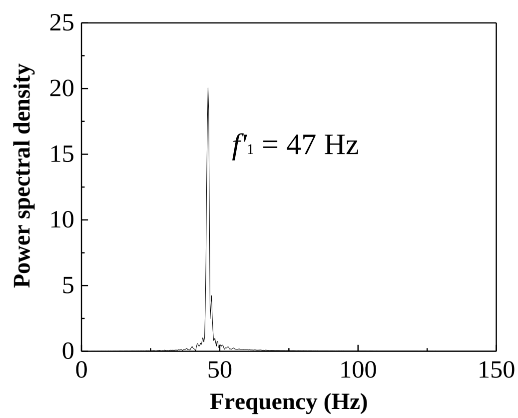
(a) Free vibration test without seismic mass



(b) Power spectral density of (a)



(c) Free vibration test with seismic mass



(b) Power spectral density of (d)

Figure 4. Free vibration tests of the GFRP panel

3. SHAKING TABLE TEST

The performance of the GFRP panel under seismic excitation is evaluated through a shaking table test. The configuration of the test is shown in Figure 5. The GFRP panel is connected to the shaking table using bolts and angles to simulate a rigid connection. The size of the angles is 10 x 10 cm, and the bolt and angle system effectively constrains the rotation in the out-of-plane direction. Both tests with and without attached mass are conducted to evaluate the dynamic responses of the wall panel.

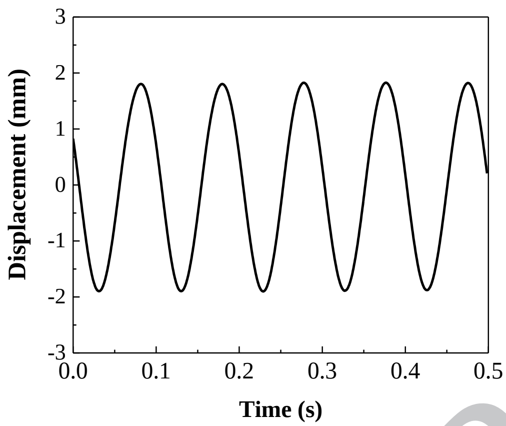
Figure 5. Shaking table test configuration

The shaking table can generate harmonic ground motions with a frequency ranging from 10 to 60 Hz. But in the test, the GFRP panel is subjected to two harmonic ground motions in the in-plane direction, as described in Table 3, since ground motions with frequencies higher than 15.1 Hz will generate accelerations greater than 3g, which would be too high for simulating real seismic ground motions. Three accelerometers and LVDTs are installed at the bottom, middle, and top of the panel to measure the displacements and accelerations. Although the ground motion displacement and displacement at other locations of the panel are harmonic, as shown in Figure 6a and b, the independently measured ground acceleration is not perfectly harmonic due to that the tests are displacement-controlled instead of acceleration controlled, as shown in Figure 6c and d. Each excitation process lasts for more than 15 seconds, long enough to produce stable and consistent results.

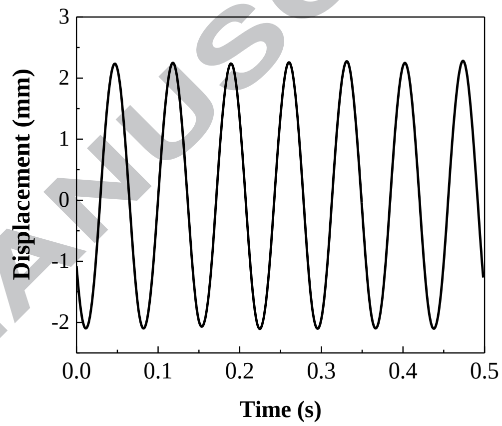
Table 3. Ground motion parameters

Ground motion	Frequency	Maximum displacement	Average acceleration amplitude
1	10.1Hz	1.83 mm	1.4 g
2	15.1Hz	1.94 mm	2.1 g

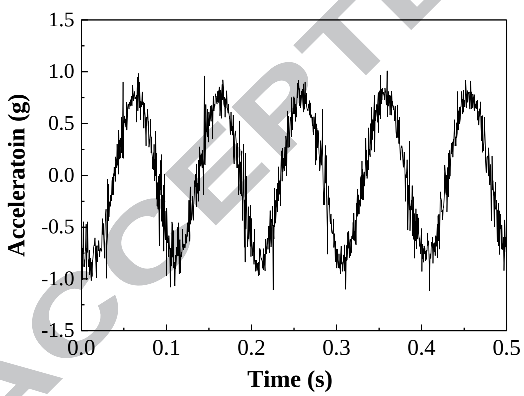
Figure 7 shows the displacements at the top of the wall panel when subjected to different ground motions. Since the hollow sectioned GFRP panel is lightweight, the displacement at the top of the wall panel is close to that from the ground motion when only the GFRP wall panel is tested. In contrast, attaching seismic weight to the wall panel significantly increases the top displacement. Also, the displacement under 15.1 Hz ground motion is much greater than that under 10.1 Hz ground motion because 15.1 Hz ground motion provides considerably larger acceleration and is closer to the natural frequency of the GFRP wall. No damage occurred during the 15.1 Hz ground motion run where the acceleration reached 2.1g. The maximum story drift of the GFRP panel recorded is 0.33%, which is smaller than allowed values of structural walls under extreme loads, mainly because of the high stiffness and the GFRP material's ability to remain linear under high strain.



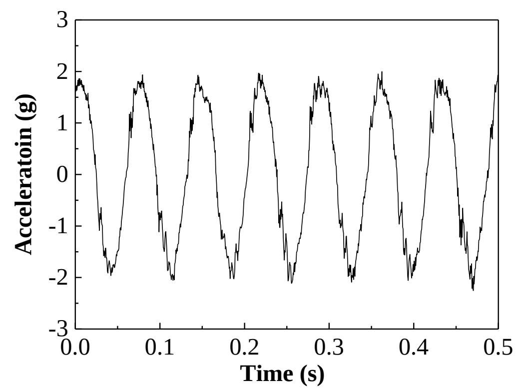
(a) 10.1 Hz ground motion displacement



(b) 15.1 Hz ground motion displacement

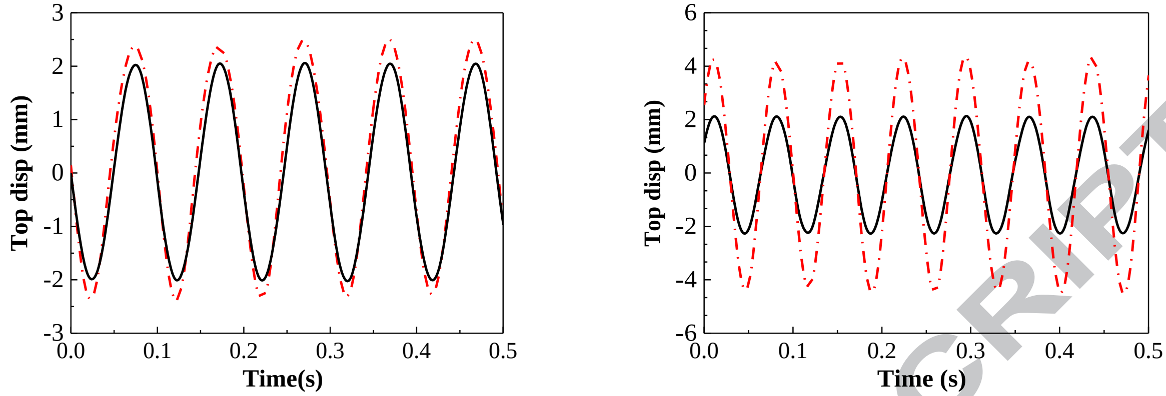


(c) 10.1 Hz ground motion acceleration



(d) 15.1 Hz ground motion acceleration

Figure 6. Shaking table test ground motions



(a) 10.1 Hz test displacement

(b) 15.1 Hz test displacement

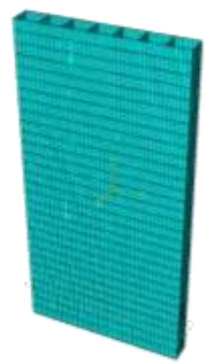
Figure 7. Shaking table test results (—— without mass –·– with mass)

4. FINITE ELEMENT ANALYSIS SIMULATION OF GFRP PANEL TESTS

FEA models are constructed using Abaqus (v6.14). Shell element S4R is used to simulate the GFRP panel, as shown in Figure 8. In the vibration analysis, GFRP pultruded structural members can be treated as elastic materials using currently available theories and computational methods [8]. Using the material properties from the test results, the GFRP material is taken as linear elastic with an elastic modulus and Poisson's ratio of 5.6 GPa and 0.27. Rayleigh damping, which is also known as proportional damping, is included in the GFRP material properties [27]. The mass proportional damping and the stiffness proportional damping factors can be calculated if both the first and the second modes are assumed to have the same damping ratio $\zeta = 0.6\%$. In the FEA model, the bottom of the GFRP panel is fixed except in the in-plane direction, which is used to apply the acceleration excitations. Table 4 compares natural frequencies obtained from the FEA models with those from shaking table tests. Satisfactory agreement is achieved, showing the linear structural characteristics of the panel.

Table 4. Comparison of natural frequencies obtained from free vibration test and FEA model

Natural frequencies	Without seismic mass attached		With seismic mass attached	
	f_1 (Hz)	f_2 (Hz)	f_1 (Hz)	f_2 (Hz)
Free vibration test	117	196	47	70
FEA model	121	201	48	72
Difference (%)	3.4%	2.6%	2.1%	2.9%

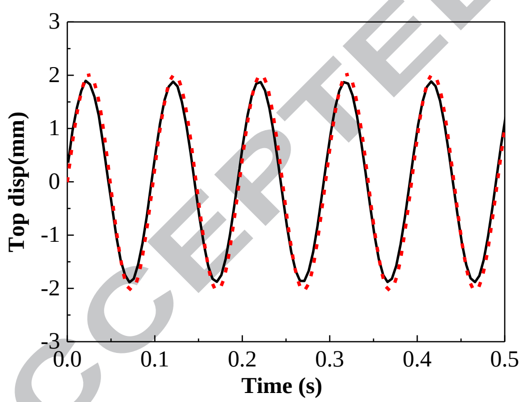


(a) GFRP panel without mass

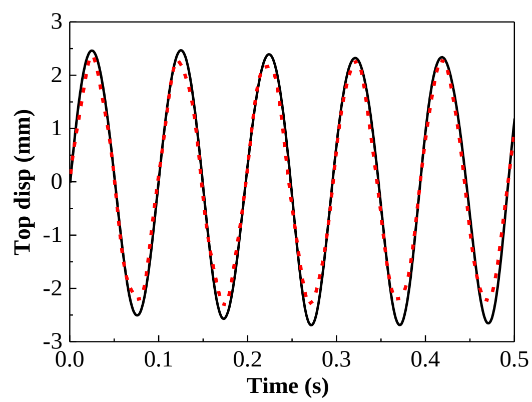
(b) GFRP panel with mass

Figure 8. Mesh of FEA model

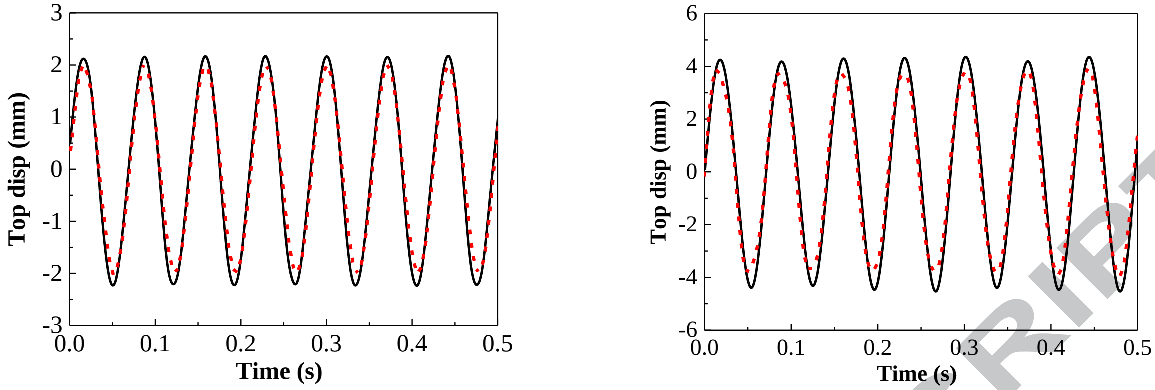
Figure 9 are plots comparing the response time histories of the FEA models with those of the test results. The errors between the FEA models and tests are within 4% and 13% for the cases with and without the attached mass, respectively. There is also a slight difference in phase for the attached mass cases, which could be attributed to the ignored damping at the mass connection. The displacement amplitudes in the experimental results are slightly larger than predicted. The difference may be explained by that the stiffness of the shaking table itself is not large enough to provide a perfect fixed boundary condition for the test specimen, and minor rotations in the in-plane direction might have happened in the dynamic tests. Overall, good agreement is found with the free vibration test and the shaking table test. The FEA result also shows that the maximum stress during the vibration is 40.2 MPa, which is smaller than the GFRP's strength 169 MPa, validating that the GFRP panel is intact during the testing.



(a) 10.1 Hz simulation without mass



(b) 10.1 Hz simulation with mass



(c) 15.1 Hz simulation without mass

(d) 15.1 Hz simulation with mass

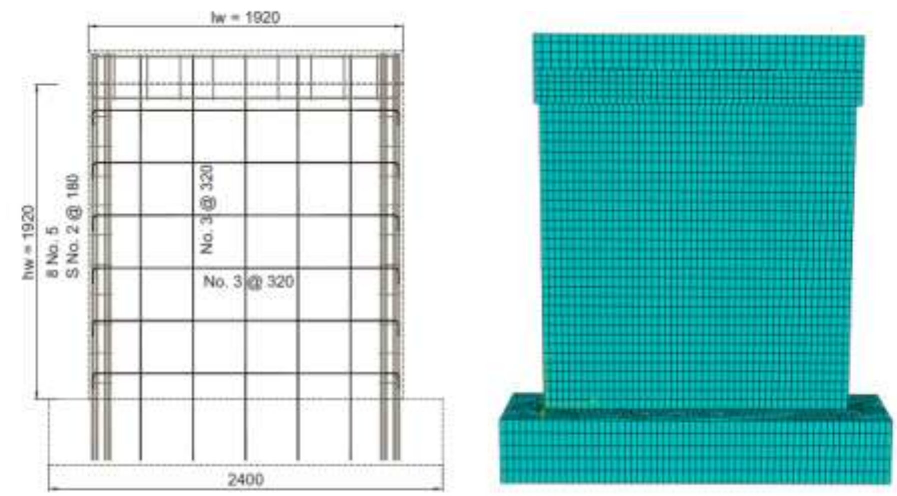
Figure 9. GFRP panel FEA simulation results (—— experimental ------ FEA simulation)

5. COMPARISON OF GFRP WALL PANEL AND RC WALL UNDER SEISMIC GROUND MOTION

Shaking table tests presented above demonstrated that the GFRP panel remained elastic under large ground accelerations. In order to further evaluate the performance of GFRP wall panel under seismic excitations, its performance is compared with structural RC walls under realistic ground motions. The selected RC wall is a 1:1.25 scale shear wall tested on a shaking table by Carrillo and Alcocer [28]. This specific RC panel is selected because it has the same thickness as the tested GFRP wall panel. In addition, the RC panel has the minimum reinforcement ratio, which is the ratio of the area of steel bars over the area of the web of the concrete cross-section, specified in ACI-318. It was originally used as a control specimen. The reinforcement layout and FEA model mesh of the 8-cm thick RC wall are illustrated in Figure 10. A single layer of No. 3 welded steel wires is placed in the middle of the RC wall web. Material properties from concrete cylinder tests and steel tension tests are summarized in Table 5. In the shaking table test, the RC wall is subjected to a recorded earthquake ground motion CA-71, which occurred in Caleta de Campos station, Mexico, on January 11, 1997 [moment magnitude (MW) = 7.1, peak ground acceleration (PGA) = 0.38 g], representing a large-amplitude earthquake event with high intensity and duration. The acceleration time history is shown in Figure 11. A seismic weight of 245 kN is selected to achieve a natural period of 0.1 sec, matching the earthquake's dominating frequency.

Table 5. Material property of the RC wall

concrete	Elastic modulus (GPa)	Compression strength (MPa)
	14.8	24.8
	Nominal yield strength (MPa)	Ultimate strength (MPa)
steel bar	412	656
steel wire	435	659



(a) Configuration in test (mm) [22] (b) FEA model in Abaqus

Figure 10. Reinforcement layout and FEA model of the concrete specimen

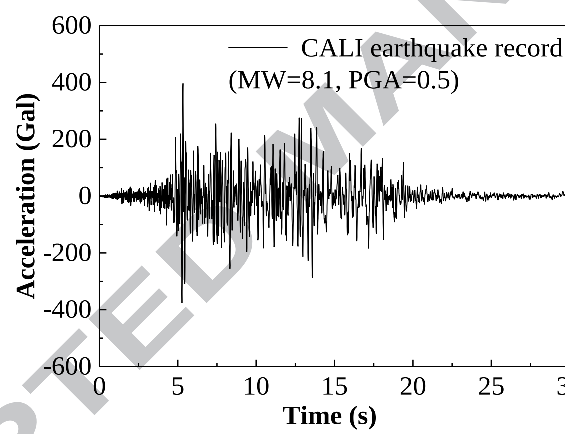
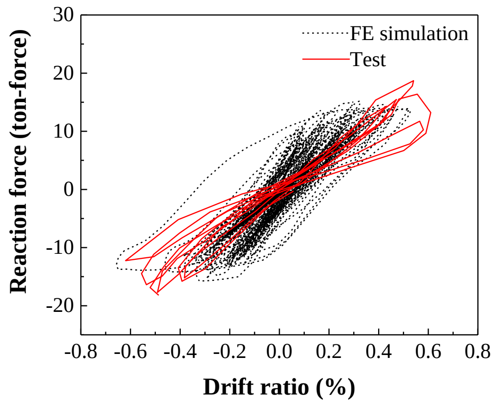


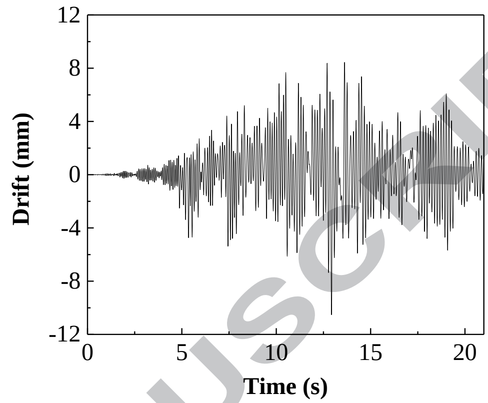
Figure 11. Time series of input seismic ground motion

An FEA model is created in Abaqus and compared to the experiment results in the RC wall research paper discussed above using its authors' test parameters. The concrete damaged plasticity model in Abaqus is adopted, which considers compression and tension damages to simulate the degradation of concrete stiffness. The steel's hysteretic behavior is modeled using kinematic plasticity. The C3D8R solid element and the T3D2 truss element are used to simulate concrete and steel bars, respectively. No slip between steel bars and concrete is considered. The concrete shear wall is rigidly fixed at the bottom and loaded in the in-plane direction with the CA-71 earthquake motion. Figure 12a shows the comparison between FEA and test results. From the time history of displacement in the dynamic explicit model, as showed in Figure 12b, the most significant concrete damage occurs at 12.9 s, forming a permanent deformation in the web of the RC wall. The FEA curve can predict the stiffness and the ultimate drift ratio of the shear RC wall under the earthquake excitation. The difference between the both data sets is caused by the approximation of concrete damage coefficients in the FEA of the concrete material model.

The exact values could be only obtained through cyclic loading test of concrete specimen. However, this information was not mentioned in Ref [28]. The largest stress, as expected, appears in the web region, which has the lowest steel ratio. Concrete damage happens near the areas where the steel bars are embedded, as illustrated in Figure 13.



(a) Comparison of hysteretic curves of test and FEA



(b) Drift time history

Figure 12. RC wall FEA simulation results

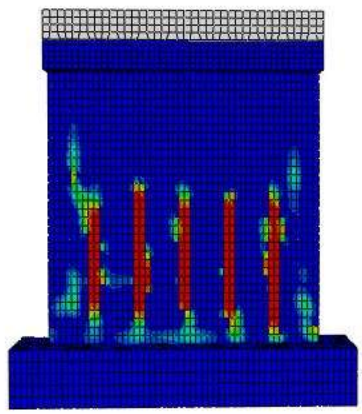


Figure 13. Concrete damage at the end of FEA simulation (red regions represent damage)

From the above results, it can be concluded that the FEA models of both RC and GFRP walls can accurately predict their dynamic behaviors. Next, to gain a better understanding of the GFRP panel's capability to resist seismic loads, a comparison of GFRP wall panel and RC wall is carried out by simulating the responses of both types of walls under earthquake motions. As mentioned above, the tested RC and GFRP walls have the same thickness of 8 cm. In this comparison, we keep the GFRP panel's cross-section unchanged, but increase its 2-D dimensions to be identical to that of the RC wall, i.e., 192 cm x 192 cm. The CA-71 earthquake record is scaled to create four different ground motions, representing low, moderate, high and ultra-high intensity earthquake events, respectively.

In the first set of comparison, the same mass block of 245 kN, representing the seismic load from a multi-story building, is attached to the top of both RC and GFRP walls. Table 6 lists PGAs for each ground motion, and the maximum drifts and stresses during the excitations. The web region in the RC wall is found to be severely damaged under both high and ultra-high intensity earthquakes. Since the failure criterion of the GFRP panel is not specified in the FEA model, the maximum stress of the GFRP panel during the high intensity ground motion reaches 213.6 MPa, which exceeds its flexural strength of 162 MPa. Therefore, the GFRP panel fails in the high intensity earthquake. The time histories of the two walls are compared in Figure 14. Due to the difference in the stiffness, the GFRP wall produces larger drifts than the RC wall. However, this difference is smaller for high and ultra-high intensity earthquakes compared to those for low and moderate intensity earthquakes, indicating that the dynamic stiffness of the RC wall under severe earthquakes deteriorates more rapidly than that of the GFRP wall.

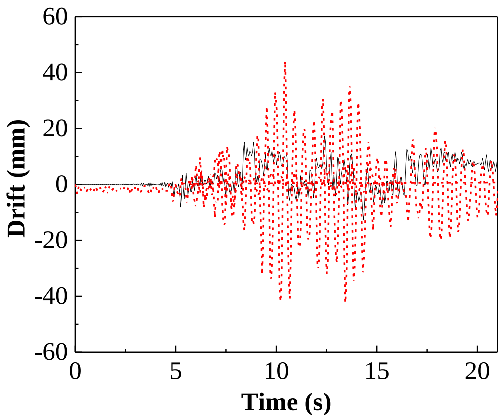
Based on the above comparison, it can be concluded that GFRP wall panels have less energy dissipation capacity than RC walls. The relatively low damping ratio of the GFRP and the lack of post-elastic behavior are its drawbacks when used as seismic-resistant structures. Another difference between the RC and GFRP walls is that the GFRP wall remains at its original position after the earthquake; while the RC wall yields, resulting in a permanent lateral deflection. Generally, GFRP wall panels do not have enough stiffness to replace RC walls in multi-story buildings.

Since pultruded GFRP structures are often low-rise and carry significantly lower seismic weight, we make another comparison of the two walls carrying a much smaller seismic mass of 4.8 kN, which corresponds to the full dead load plus 20% of the snow load, as listed in Table 2, for a one-story building. In this case, the maximum stress and drift of the two walls become much smaller, as illustrated in Table 7, showing that both walls are in elastic range. Generally, the maximum stress and drift are proportional to the seismic excitation acceleration. The maximum stress of GFRP wall is 5.4 MPa, which is much lower than its lengthwise flexural strength of 162 MPa. The RC wall still has lower stress and drift ratio due to its larger stiffness, as shown in Figure 15. However, the performances of the two walls are closer compared to those for multi-story buildings. Since the GFRP wall panel has much smaller self-weight and higher strength, it can be considered as a viable solution for low-rise buildings in seismic zones.

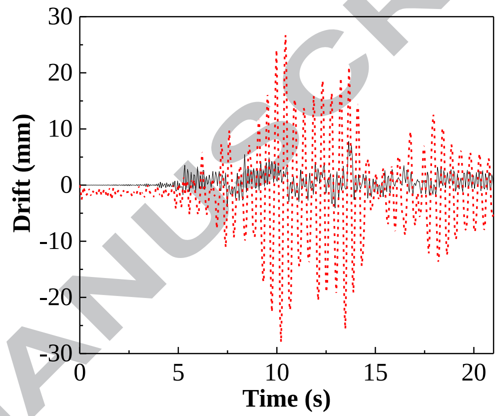
Parametric studies are conducted to better understand the GFRP wall panels' application. First, shell thicknesses are varied to investigate how much the GFRP panel's section increase is needed to match the RC wall's dynamic stiffness. In the FEA model, the shell thicknesses of GFRP panel are doubled and tripled, and then they are compared to the RC wall with a seismic load of 245 kN under the high intensity ground motion. The results listed in Table 8 show that the GFRP's shell thicknesses need to be increased three times to achieve similar deflection of RC walls. This may pose a challenge in FRP fabrication. Another parameter studied is the seismic weight attached on the top the panel. The maximum stresses and drifts under the high intensity ground motion are listed in Table 9, which indicates that, in order for the GFRP panel's stress and drift to be within a reasonable range, the supported seismic weight on the panel should be less than 96 kN. This weight approximately corresponds to a three-story residential building.

Table 6. Comparisons of maximum stress and drift under the seismic load of 245 kN

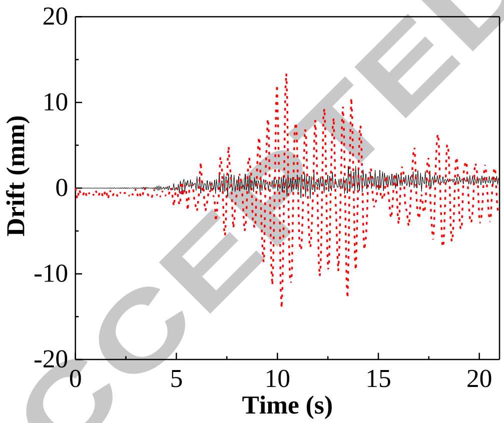
Ground motion	PGA(g)	RC wall		GFRP panel	
		Maximum stress (MPa)	Maximum drift (mm)	Maximum stress (MPa)	Maximum drift (mm)
Low intensity	0.10	17.8	1.5	40.4	7.0
Moderate intensity	0.20	24.2	2.5	81.1	14.0
High intensity	0.40	24.8	10.2	172.8	26.8
Ultra-high intensity	0.60	24.8	17.8	213.6	44.2



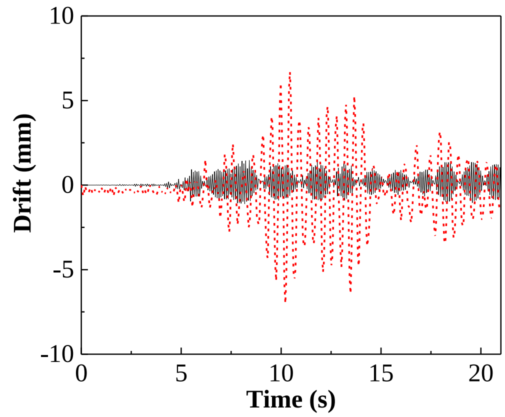
(a) Drift of walls under ultra-high intensity



(b) Drift of walls under high intensity



(c) Drift of walls under middle intensity

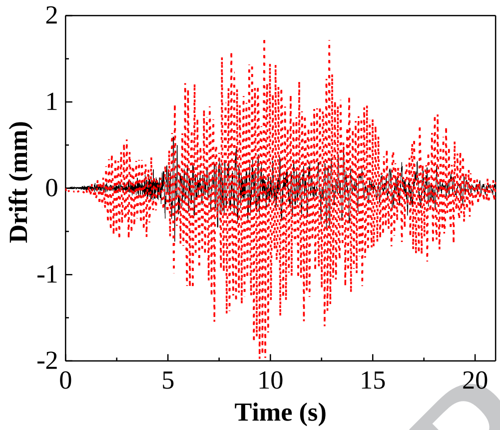


(d) Drift of walls under low intensity

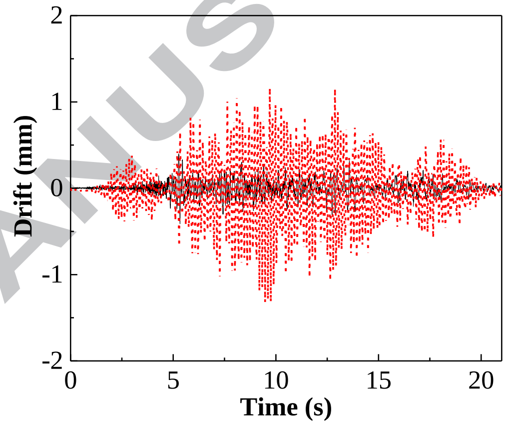
Figure 14. Comparisons of time histories of drifts under the seismic load of 245 kN
(——— RC wall -·-·-GFRP wall panel)

Table 7. Comparisons of maximum stress and drift under the seismic load of 4.8 kN

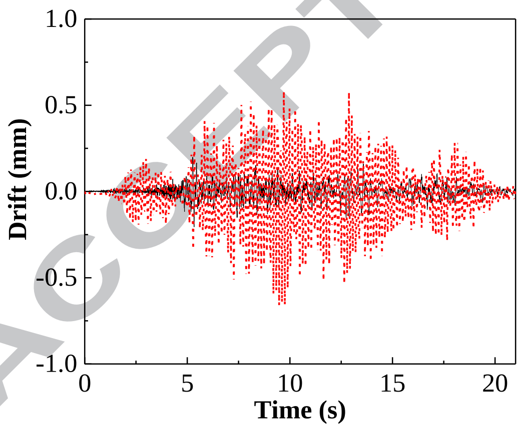
Ground motion	PGA(g)	RC wall		GFRP panel	
		Maximum stress (MPa)	Maximum drift (mm)	Maximum stress (MPa)	Maximum drift (mm)
Low intensity	0.10	0.56	0.10	1.3	0.34
Moderate intensity	0.20	0.99	0.20	2.4	0.69
High intensity	0.40	1.97	0.41	4.1	1.35
Ultra-high intensity	0.60	2.92	0.61	5.4	1.97



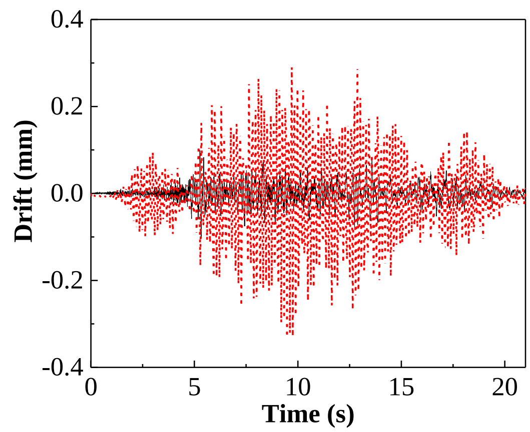
(a) Drift of walls under ultra-high intensity



(b) Drift of walls under high intensity



(c) Drift of walls under middle intensity



(d) Drift of walls under low intensity

Figure 15. Comparisons of time histories of drifts under the seismic load of 4.8 kN
(——— RC wall - · - · -GFRP wall panel)

Table 8. Parametric study of the GFRP panel's shell thickness

Specimen	Maximum stress (MPa)	Maximum drift (mm)
GFRP panel with original thickness	172.8	26.8
GFRP panel with double thickness	95.6	18.2
GFRP panel with triple thickness	60.3	10.6
RC wall	24.8	10.2

Table 9. Parametric study of the supported seismic load on the top of the GFRP panel

Supported seismic load	Maximum stress (MPa)	Maximum drift (mm)
4.8 kN	4.1	1.35
48 kN	38.7	9.6
96 kN	75.8	16.2
142 kN	111.6	21.4
245 kN	172.8	26.8

6. CONCLUSIONS

Dynamic behavior of a pultruded GFRP wall panel is experimentally and numerically examined. Free vibration tests of the panel indicates their higher natural frequencies and lower damping ratios than other types of traditional structural walls. The GFRP panel in the shaking table tests exhibits good resistance to the seismic load due to its high strength and lightweight despite the high intensity of input ground motion, indicating that GFRP panels have a potential to be used as seismic-resistant structural walls.

FEA models are created to correlate the displacement time history of the GFRP panel from shaking table test. The same method is applied to model a traditional RC shear wall under earthquake excitations in literature. Both models achieve good correlations with experimental results. After comparing their performances under seismic loads, we can conclude that, when applied to multi-story buildings, RC walls tend to have smaller drift and higher energy dissipation capacity compared to GFRP walls. Therefore, RC walls remain a better option. However, when designed as shear walls for low-rise buildings, the deformation and the maximum stress of the RC and GFRP walls are closer compared to those for multi-story buildings. Parametric study shows that the GFRP walls can support seismic weight of buildings with no more than three stories. Due to its elastic behavior, the performance of the GFRP wall panel is more predictable. In addition, it has low self-weight and high strength and is easier for post-earthquake repair and replacement, which makes the GFRP wall panel a viable solution for low-rise buildings in seismic zones.

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